Advanced Ultrafast Laser Concepts at the Tens of Terawatt Level

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Abstract

The Laser Plasma Laboratory’s multi-terawatt femtosecond laser (MTFL) will be undergoing a laser upgrade in the upcoming months. The current chirped pulse amplification system will be upgraded from 25 mJ to 500 mJ. Amplification processes at high intensities such as these introduce the problem of gain narrowing. Fastlite’s DAZZLER (an AOPDF) was used to shape the laser pulse before amplification in order to avoid the effects of gain narrowing. This increased the bandwidth from 19 nm to ~34 nm, which should correspond to a peak power increase of 10 TW to 17.8 TW when the laser upgrade is complete. An automated program was created such that the parameters of the pulse shape can be found and implemented during daily use of the upgraded MTFL.

INTRODUCTION

The multi-terawatt femtosecond laser (MTFL) will be an upgrade of the existing Ti:Sapphire chirped pulse amplification (CPA) system (Fig. 1). The pulse energy will be increased from 25 mJ to 500 mJ. The chirped pulse amplification system operates by temporally stretching each laser pulse before amplification, and compressing it again after amplification. This technique is used to avoid the nonlinear effects of the gain medium. If the pulse is left unstretched, the high intensity of the pulse’s peak can damage the crystal’s gain medium, in addition to encountering the issue of self-focusing (the higher intensity ‘sees’ a higher index of refraction, and acts as a lens). After being stretched, the MTFL pulses will be amplified through a regenerative amplifier followed by two multi-pass Ti:Sapphire amplifying crystals. This will amplify the pulse energy from a few nJ to 500 mJ. The pulses will then be compressed into higher intensities. The stretchers and compressors in the case of the MTFL are high-density diffraction gratings.

The planning of this system upgrade required an accurate amplification model. The model was used to determine the best seed and pump diameters to match the beam fluence with
the number of passes made through the crystal amplifier. This ensured optimal operational intensities and B-integral, also avoiding the damage threshold.

The planning process for the MTFL upgrade also involved compensation methods for gain narrowing. Gain narrowing reduces the bandwidth of the spectrum with each pass through the crystal. As the pulses pass through the crystal, the higher intensities in the Gaussian spectrum get amplified more than the lower intensity ‘wings’ of the spectrum due to a nonlinear effect, resulting in a significantly narrower spectrum (Fig. 2).

![Amplified Spectra at each Pass](image1)
![FWHM at each Pass](image2)

**Figure 2: Gain Narrowing - 50 passes shown**

Gain narrowing is an unwanted effect, as it increases the pulse duration according to the transform-limit [Eq. 1], which in turn decreases the peak power output.

\[ \Delta \tau \Delta \nu = 0.441 \]

The gain narrowing effect was numerically coded in a MATLAB model before practical measures were taken to counter it. Once convinced that the model was accurate, an acousto-optic programmable dispersive filter (the Fastlite DAZZLER) was used to shape the pulse before it was amplified. A ‘dip’ was placed in the center of the Gaussian spectrum before the pulses were amplified. This resulted in significantly less gain narrowing, as desired. This method was then automated in a LabVIEW interface in order to enable future MTFL users to daily pick the best ‘dip’ parameters for the Dazzler to implement in the pulse spectrum.

The Dazzler pulse-shaping will be necessary in order to obtain a pulse duration below 30 femtoseconds that will ideally result in peak powers over 15 TW.

**EXPERIMENTAL METHODS**

The methods to avoid gain narrowing began with a MATLAB model. This model allowed for variable input pulse shape, so that the user could adjust the input pulse to include a “dip” in the Gaussian profile. This reduces the amplitude at the center wavelength, meaning that the profile as a whole experiences significantly less gain narrowing. Figure 3 demonstrates the MATLAB model at work, displaying a non-physical example of such a pulse getting amplified.
The spectrum has a fairly substantial dip, but after passing through the crystal 50 times, it ends up having fully recovered its Gaussian spectrum, this time with a wider bandwidth than when modeled without the dip. This confirmed the strategy of pulse-shaping before amplification to avoid gain narrowing.

With the confirmation of pulse-shaping being a promising method, the DAZZLER was then implemented. The DAZZLER is an acousto-optic programmable dispersive filter (AOPDF) designed by Fastlite (Fig. 4). The exact inner workings of the DAZZLER are kept fairly private by the company, as it sells the only product in the world exactly like this. It is similar to an acousto-optic modulator, in the sense that it uses sound waves as a diffraction grating. As the longitudinal sound wave propagates through air, the compression and decompression of the air molecules slightly changes the index of refraction at those points, causing an intense light beam such as a laser to act as though hitting a Bragg grating if it is the corresponding wavelength to the period of the sound wave. The intensity of the sound wave determines how much of that input spectrum’s wavelength will be diffracted. The DAZZLER interface allows the user to adjust the parameters such that the diffracted beam profile will have a customized “dip.”
The DAZZLER is implemented into the MTFL scheme to counter gain narrowing by placing it before the stretcher in the CPA system (Fig. 5).

![Figure 5: Countering Gain Narrowing - Set-Up Scheme](image)

The first step in the experimental method was simply to adjust the “dip” parameters, manually taking a spectrum after the regenerative amplifier (the current set-up) to monitor how each parameter change adjusted the final spectrum. The data was then analyzed by hand to find an increase from 19 nm (amplified without the “dip”) to over 30 nm (the amplified spectrum with the highest FWHM). Although the dispersion of the beam has not yet been accounted for, this should correspond to a decrease in pulse duration from 50 fs to under 30 fs. In turn, this will increase the peak power from 10 TW to > 17 TW, assuming an amplified pulse energy of 500 mJ, which should be the pulse energy of the upgraded laser.

Thus, using the DAZZLER turned out to be a success. However, the best “dip” parameters do not stay constant, as the seed laser is not always consistent, due to environmental differences, etcetera. It is anticipated that the upgraded system would experience the same changes. Taking a large amount of data by hand every day simply to discover the best parameters for the DAZZLER would be a daunting and annoying task. Therefore, the series was automated. A LabVIEW interface was designed to be run daily in order to collect varied spectra, and then analyzed to discover the best spectrum (Fig. 6).
The first LabVIEW program was used to take data: a series of spectra after the amplification, to be analyzed for best parameters. This program cycled through the DAZZLER “dip” parameters, having the start, end, and increment parameters selected by the user (Fig. 7). Each time one parameter is changed, the spectrum after the amplifiers is saved. The number of data files that will be saved during the running of the program is listed, and a progress bar is displayed as the data is obtained.

A different LabVIEW program was then written to analyze the fresh data (Fig. 8), providing the user with the best parameters for the highest bandwidths with the closest matches to a Gaussian profile. The user adjusts what maximum error (with respect to a Gaussian) he is willing to accept, in addition to the minimum FWHM. This limits the number of spectra left to sift through manually. The user is then able to scroll through these best fits, picking the most satisfactory spectrum “dip” parameters to input in the DAZZLER that day.
Successful utilization of these LabVIEW programs should result in a satisfactory reduction in gain narrowing for the MTFL on a regular basis.

RESULTS

The DAZZLER successfully countered gain narrowing. The best FWHM is 33.5 nm, compared to the 19 nm when the gain narrowing was left un-countered. Assuming all goes well in the MTFL upgrade, such an end FWHM result means a decrease in pulse duration from 50 fs to 28 fs and an increase in peak power from 10 TW to 17.8 TW. (Fig. 9)
The LabVIEW programs were also completed successfully, meaning that once the MTFL is upgraded, the DAZZLER’s best parameters can be selected quickly whenever necessary. This saves time and effort on the part of the future MTFL users.

CONCLUSIONS

In conclusion, the decreased transform-limited pulse duration below 30 fs will enable an increase in MTFL peak power from 10 TW to > 17 TW. The LabVIEW programs will also optimize the spectrum on demand.

Future work will include implementing this design when the MTFL is upgraded. It could also include creating a feedback loop for the LabVIEW programs, using a more complex genetic algorithm for the DAZZLER parameters, or the possibility of using a MAZZLER instead of the DAZZLER (this piece is positioned in the cavity instead of before the stretcher).

ACKNOWLEDGMENTS

I would like to thank Andreas Vaupel, Benjamin Webb, Nathan Bodnar, and Dr. Lawrence Shah for their help and guidance during this project.

I would also like to acknowledge the National Science Foundation for the REU funding of this project.

REFERENCES
